

Article

Environmental Implications of Agricultural Practices Among Smallholders: The Case of Biofertilizer Production for Forage Oat Cultivation

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Abstract

Biofertilizers are often presented as a more ecological alternative that allows for the utilization of agricultural residues and reduces dependence on chemical fertilizers. This study uses the life cycle assessment (LCA) methodology to analyze the environmental implications of producing forage oats on a small scale, considering three fertilization strategies: (1) application of a biofertilizer, (2) application of an inorganic fertilizer, and (3) no fertilization. Two functional units (FUs) were evaluated within a cradle-to-farm-gate system boundary: one ton of oats and one harvested hectare. The results show that while forage oat production using inorganic fertilizers yields a high output (6.20 t/ha of oat dry matter), it also results in the most significant environmental impacts across both FUs (e.g., 262 kg Carbon dioxide equivalent (CO₂ eq)/ton and 1620 kg CO₂ eq/ha). In contrast, using biofertilizers increases the yield to 7.05 t/ha of oat dry matter while decreasing environmental impacts (e.g., 80.1 kg CO₂ eq/ton and 564 kg CO₂ eq/ha). Finally, when no fertilization is used, the yield decreases significantly (4.92 t/ha of oat dry matter), while the environmental performance varies depending on the FU considered (e.g., 98.1 kg CO₂ eq/ton and 482 kg CO₂ eq/ha). This study shows that, compared to inorganic fertilization or no fertilization at all, biofertilizers optimize both production and environmental performance. Therefore, biofertilization is a key strategy for managing residues and reducing environmental impacts in this case study.

Keywords: forage; livestock manure; life cycle assessment; circular economy



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1. Introduction

Climate change has a negative impact on agricultural productivity, particularly in developing and poor countries [1]. In 2020, global greenhouse gas (GHG) emissions from agrifood systems reached 52 Gt of CO₂ eq, only 2 Gt less than those reported in 2019. These emissions were linked primarily due to COVID-19-related economic contraction, although they still remain 34% higher than in 2000 [2].

Latin America (LA) is recognized as one of the world's leading food exporters [3]. In this region, Mexico is one of the most important agricultural countries, second only to Brazil and Argentina, generating 67 billion dollars from the agricultural sector [4]. In northwestern Mexico, oat represents an essential crop for a balanced livestock diet and its consumption is expected to increase from 10.6 in 2016 to 12.7 Mt by 2030 [5]. Specifically, in El Mezquital, Durango, oat appears as the second most important crop, increasing its harvested area and production from 492 to 1524 ha and from 9840 to 15,756 t, respectively, during the last 10 years [6]. However, the increasing demand forces farmers to increase the use of inorganic agrochemicals to enhance growth and production.

Effective nutrient management is crucial for farmers, due to the trend of declining soil fertility associated with continuous land use [7], intensive tillage, and the application of inorganic fertilizers [8]. Nitrogen (N) is one of the most important and common nutrients in crop production. For instance, in Mexico, the consumption of inorganic fertilizers during 2022 reached 1.5 Mt, where nitrogenated fertilizers accounted for up to 63% of the total national consumption [9]. However, plants usually assimilate only a small fraction of N contained in fertilizers, while the remaining N may be volatilized, leached, or converted by microorganisms into nitrous oxide (N₂O) as a metabolic by-product [10]. These processes are intensified due to an over-utilization of N-fertilizers from inorganic fertilizers producing several environmental impacts, including soil degradation, contamination, and a decrease in the quality of water and air resources, as well as biodiversity loss [11,12]. Therefore, organic alternatives such as biofertilizers have been become widespread, aiming to reduce environmental pressure while optimizing the use of organic residues during agricultural production [13].

Biofertilizers have appeared as a suitable alternative to inorganic fertilizers, increasing nutrient availability in the soil by promoting nitrogen fixation, soluble phosphorus, and mobilizing essential nutrients for optimal plant development [14]. In this regard, cow manure is frequently used as a biofertilizer; nevertheless, it contains high concentrations of organic matter and nutrients, which may compromise the growth and health of plants when it is not properly applied [15]. Because of this, the anaerobic digestion (AD) process is used to mitigate the negative impacts of manure direct application and facilitate sustainable waste management by recycling nutrients and energy [16]. The digested material produced in the AD process as a by-product is named digestate, which can be applied as a biofertilizer [17]. Digestate contains a considerable concentration of stable and soluble nutrients, including ammonium nitrogen (NH₄), phosphorus pentoxide (P₂O₅), and potassium oxide (K₂O) [18]. Moreover, the presence of microbial communities and enzymes in digestate impacts the structural integrity, aeration, and drainage of the soil, which promote plant growth [19].

The recovery and valorization of residues, such as manure and organic matter in an agricultural context, present viable alternatives for reducing negative environmental impacts [20]. LCA is widely recognized as a methodology to assess the potential environmental impacts of products, processes, or services by comprehensively evaluating the inputs and outputs within a production system, considering the process from raw material extraction to its final disposal [21]. Additionally, LCA highlights environmental hotspots that significantly influence overall impacts, facilitating the identification of more sustainable alternatives [22].

In the context of oat production, several LCA studies have been identified; however, these focused on oat grain production [23], oat straw [24], oat flakes [25,26], and food generation from oat proteins [27,28] in forage oat production. Hietala et al. [29] assessed the impact of global warming (GW) and water scarcity on various cereals in Finland, including oats. However, the environmental impacts of forage crop production are generally assessed as part of the LCA of livestock production. Similarly, Perez-Vega et al. [30] evaluated the environmental impact of producing 1 kg of an oat-based food prepared using a three-phase ultrasonic-assisted partitioning process, whereas Kytä et al. [31] evaluated the GW of various organic fertilizers for oat grain production using three different FUs: one ha, one ton of grain produced, and one kg of N applied. Nevertheless, the available information is limited regarding the production of forage oats and the potential environmental impacts of using biofertilizer from manure in forage oat production, as well as the LCA linked to its production. Therefore, this study aims to evaluate the potential environmental impacts in forage oat production by fertilizing with a self-produced biofertilizer in El Mezquital, Durango, and to compare these results with those of common cultivation practices in the region.

2. Materials and Methods

This study was conducted following the ISO 14040:2006 guidelines [21,32], which encompass four distinct phases of the LCA methodology. Consequently, this section is divided into the following subsections: (i) case study; (ii) goal and scope definition; (iii) life cycle inventory; (iv) life cycle impact assessment.

2.1. Case Study

Data were collected from a rural farm in the municipality of El Mezquital, Durango, Mexico (23°36'43.3" N, 104°21'44.5" W), during the year 2023. The average annual temperature and precipitation were 19.2 °C and 650 mm, respectively [33], while the monthly temperatures and precipitation for this year are presented in Table S1.

Three different scenarios for forage oat production were analyzed in this study, each with a different fertilizer dose. Data for Scenarios 1 and 3 were taken from Aguirre-Córdova et al. [34], who evaluated the application of biofertilizers at different dosages. Their study reports the methods for soil characterization and sampling, biofertilizer characterization, forage oat (*Avena Sativa* L.) production and sampling, the experimental design used to evaluate the biofertilizers, and the associated statistical analyses. The detailed soil nutrient composition was previously reported by Aguirre-Córdova et al. [34] and a summary of it is presented in Table S2, along with the biofertilizer chemical composition in Table S3. Scenario 2 followed the same guidelines as in Aguirre-Córdova et al. [34] to quantify production, representing the common inorganic fertilization practices in the rural region of El Mezquital. These practices are not based on soil analysis or the crop's nutritional requirements; therefore, they are not nutritionally equivalent to the other scenarios, as shown in Table S4.

Scenario 1: It considers 880 L/ha of self-produced biofertilizer, resulting in a yield of 7.05 t/ha of oat dry matter. The biofertilizer was produced in an anaerobic digester and filled with water and cow manure at a 1:5 dilution rate, respectively. The process was carried out at 25 °C, and a solar boiler attached to the anaerobic digester helped to maintain internal temperature within the mesophilic range. Then, the biofertilizer was applied twice, with a half-dose administered at each application.

Scenario 2: It evaluates the use of inorganic fertilizer according to the typical dosage used by producers, 150 kg/ha of urea (CO(NH₂)₂), leading to a yield of 6.20 t/ha of oat dry matter.

Scenario 3: It considers the forage oat production without the addition of any fertilizer, resulting in a production of 4.92 t/ha of oat dry matter.

2.2. Goal and Scope Definition

This research aimed to determine the environmental implications of forage oat production fertilized with on-farm biofertilizer derived from cow manure, ranging from the collection of manure by small producers to the harvesting of oat crops, while comparing it with conventional fertilization practices employed by the producers and oat production without using fertilizers. Therefore, a cradle-to-farm-gate system boundary was used, considering the stages of manure collection, its anaerobic digesting process, biofertilizer transportation, and other agricultural activities, including direct field emissions (Figure 1). The FU of this analysis was one ton of oat produced. In addition, one hectare of harvested oat was also evaluated as an FU to evaluate the influence of the oat yield on the environmental impacts.

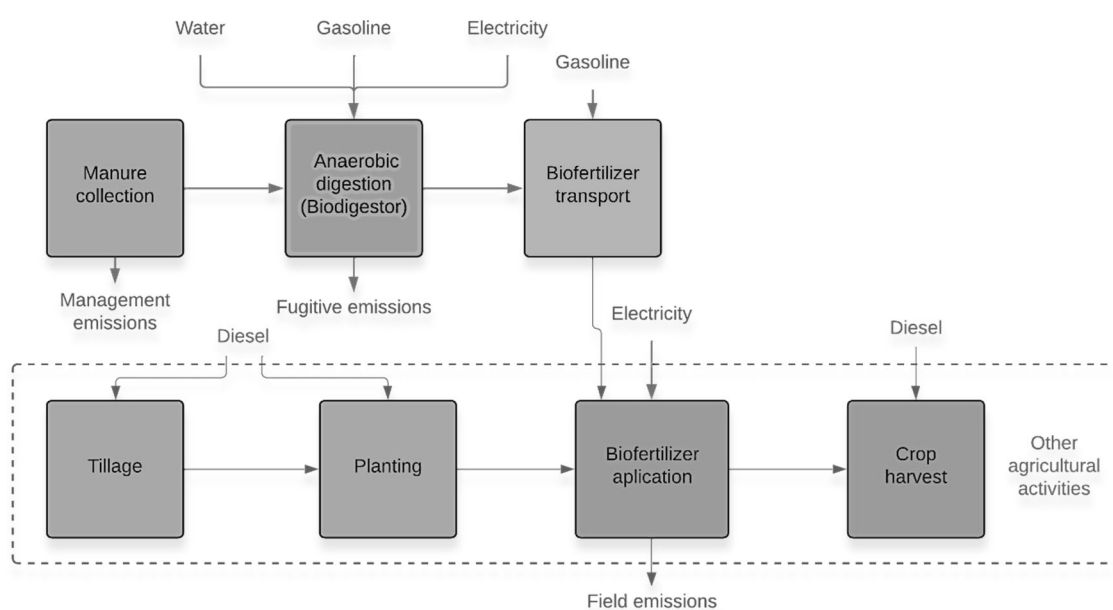


Figure 1. System boundaries of oat production.

2.3. Life Cycle Inventory

The operational data acquisition process was facilitated through an experimental in situ phase. At the same time, some data that could not be gathered directly from farms were sourced from existing literature and relevant databases. Table 1 presents the inventory obtained.

Table 1. Life cycle inventory of forage oat production per hectare.

Stage	Flow	Amount	Unit
Manure collection	Inputs		
	Manure, solid, cattle	2.20×10^2	kg
	Outputs		
	Ammonia infiltration	8.25×10^{-2}	kg
	Dinitrogen monoxide indirect air	1.53×10^{-6}	kg
	Dinitrogen monoxide direct air	2.55×10^{-5}	kg
	Dinitrogen monoxide leached	7.64×10^{-7}	kg
	Methane, biogenic	2.77×10^{-9}	kg

Table 1. Cont.

Stage	Flow	Amount	Unit
Anaerobic digestion	Inputs		
	Digester *	2.08×10^{-4}	Item
	Electricity	3.67×10^{-2}	kWh
	Naphtha	1.18×10^{-1}	kg
	Water, river, MX	8.80×10^{-1}	m ³
	Outputs		
	Carbon dioxide, biogenic	3.11×10^0	kg
	Methane, biogenic	2.66×10^0	kg
Biol Transport	Sulfuric acid	2.86×10^3	mg
	Inputs		
	Naphtha	7.10×10^{-1}	kg
Biofertilizer application	Inputs		
	Electricity	1.59×10^{-2}	kWh
	Outputs		
	Ammonia	1.10×10^{-2}	kg
	Dinitrogen monoxide	9.56×10^{-1}	kg
	Nitrate	1.07×10^2	kg
	Nitrogen monoxide	5.69×10^{-3}	kg
	Phosphorus leach to grow water	7.00×10^{-2}	kg
	Phosphorus run-off to surface water	1.75×10^{-1}	kg
	Phosphorus erosion to river	1.88×10^{-1}	kg
Other agricultural activities (tillage, planting, and harvesting)	Inputs		
	Diesel, burned in agricultural machinery	1.62×10^2	kWh
	Oat seed, for sowing	1.20×10^2	kg
	Polyethylene, low density, granulate	1.70×10^1	kg
	Wire drawing, steel	4.30×10^1	kg

Note: * Inputs for the manufacturing of the anaerobic digester included: aluminum (5.00×10^{-1} kg); chromium steel pipe (9.68×10^1 kg); diesel for machine operation for 2 h; naphtha (3.50×10^1 kg); high density polyethylene (3.71×10^2 kg); solar collector system (1 Item).

2.3.1. Manure Collection

Manure was collected in the small producers' pens located 10 m away from the anaerobic digester. This activity was carried out by hand with a wheelbarrow and shovel, every three days for a month. The rest of the time, manure was spread to nearby fields. The collected manure was transported and loaded into the anaerobic digester. During this stage, direct and indirect emissions to the atmosphere, as well as those of N₂O and methane (CH₄) generated by manure management, were considered according to Tier 1 guidelines of the IPCC [35], due to data availability. The infiltration of ammonia into groundwater was estimated according to Brentrup et al. [36].

2.3.2. Anaerobic Digestion

AD was performed in a digester constructed from a high-density polyethylene (HDPE) geomembrane, supported by a framework of low-carbon steel square tubes and electro-galvanized welded mesh. It incorporates a gasometer made of a geomembrane for biogas storage with an inlet and outlet of 2" PVC pipes. The digester measures were 6.5 m in

diameter and 2.5 m in height, offering a total volumetric capacity of 82 m³ and a maximum operational volume of 70 m³. A useful lifespan of 20 years was considered with an annual biofertilizer production of 240 m³. In addition, it is equipped with a 7 hp gasoline pump for recirculation and a ½ hp pressurizing pump that circulates water from a domestic solar heater, ensuring a constant inner temperature during the night period. Inputs related to the digester's construction per FU, considering its operational lifespan, are detailed in Table 1 and denoted by an asterisk. The digester was fed with cow manure for approximately one month; the digestion process lasted 60 days. The biofertilizer was stored inside the digester, and only the necessary amount was released through the outlet valve.

During the AD process, diffuse CH₄ emissions occurred from various components, including the digester itself, the piping, storage systems, and treatment devices. These emissions were considered to be 1.3% of the CH₄ production from the digester [37,38]. Additionally, emissions associated with the anaerobic digester, gasoline consumption of the recirculating pump, and energy of the pressurized pump were considered.

The digester was built for the production of biofertilizer, while a marginal amount of biogas was considered a by-product used for cooking by the producers or burned off. During the whole season, 52 m³ of biogas was generated with an average composition of 50% CH₄, 40% CO₂, and 250 ppm H₂S. Thus, emissions related to biogas combustion were not included, as those were considered climate neutral and no allocation was made. The carbon dioxide produced was part of the natural carbon cycle and does not contribute to an increase in atmospheric carbon levels [39].

2.3.3. Biofertilizer Transport

The biofertilizer obtained from the AD process was further transported to a farm located 5 km away. For this, an average performance of the truck engine of 6 km per liter of gasoline was considered. This transport activity took place twice per cycle.

2.3.4. Biofertilizer Application

Foliar application of the biofertilizer through a battery-powered backpack sprayer with a capacity of 4 Ah was conducted. The quantified emissions of this stage were related to emissions generated by oat crops and associated emissions with the application of fertilizers. Nitrogen emissions considered in this study were N₂O, NO, NO₃, and NH₃, and were estimated using the Indigo-Nv3 model tested by Bockstaller et al. [40]. This model allows for the quantification of field emissions derived from nitrogen fertilizers, as well as emissions resulting from soil conditions and agricultural management strategies, taking into account the crops and agro-climatic parameters described in this manuscript and detailed in Table S4 as a final result. The field emissions based on the aforementioned factors are presented in Table S5. In addition, field emissions from phosphorus (P₂O₅) were considered as P leached to groundwater, P lost through run-off to rivers, and P emitted through erosion to rivers, and were calculated following the SALCA-P model [41–43]. This model allows phosphorus emissions from agricultural systems to be quantified. By estimating phosphorus losses into the environment (soil, run-off and, in groundwater by leaching). For their emission calculation the values from Tables S1–S3 were used. Regarding P emissions to rivers via soil erosion, both the 50 m plot length and the specific agricultural practices employed, i.e., strip cropping across the slope, were taken into account, considering a plot slope of 0.2%. Foliar application of fertilizers shows significant advantages for agricultural production by providing essential nutrients when soil conditions prevent root absorption and enhancing application efficiency due to reduced volumes required for supplying a portion of the required nitrogen for plant growth [44].

2.3.5. Other Agricultural Activities

Oat cultivation also includes the agricultural activities of tillage, planting, and harvesting. The oats were planted on the plot after a corn cycle. Tillage was carried out with a tractor (55 kW) to eliminate weeds in the plot and prepare the soil for planting. Planting was done by hand at a rate of 120 kg/ha, which was subsequently covered by turning the ground with the tractor. Seven irrigations were carried out in flooded furrows, using 100 mm of water each time, with water from the El Mezquital River channeled through a community irrigation ditch. These irrigations were not included in the water consumption calculations, as consumption is the same in all three scenarios and reflects the community's usual practices. Ditch water is managed collectively, and farmers typically have access to it for their plots every 15 days on average. Finally, harvesting was carried out by cutting and baling the oats for further storage.

2.4. Life Cycle Impact Assessment

The environmental impacts were modeled using the OpenLCA v.2.0.1 software [45], whereas the background data were obtained from the Ecoinvent v.3.8.1 database [46]. The life cycle impact assessment method ReCiPe midpoint (H) [47] was used to evaluate fine formation of particulate matter (FPM), fossil resource scarcity (FRS), freshwater ecotoxicity (FW ecot), freshwater eutrophication (FW eutro), global warming (GW), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HnCT), ionizing radiation (IR), land use (LU), marine ecotoxicity (M ecot), marine eutrophication (M eutro), mineral resource scarcity (MRS), ozone formation human health (OFHh), ozone formation terrestrial ecosystems (OFTe), stratospheric ozone depletion (SOD), terrestrial acidification (TA), terrestrial ecotoxicity (TE) and water consumption (WC).

3. Results

3.1. Environmental Impacts of Oat Production

Figure 2 shows the contribution of each agricultural stage to the environmental impacts under Scenario 1. The biofertilizer application was the main contributor (more than 50% each) in the categories of FPM, FW eutro, GW, OFHh, OFTe, SOD, and TA, mainly due to the field nitrogen emissions, as well as nutrients that leach and are washed away into surface waters. This finding is comparable to the results reported by Parajuli et al. [48], who analyzed GW using LCA for maize, grass clover, ryegrass, and winter straw. Their study indicated that between 36% and 46% of the reported GW was related to crop nitrogen emissions, while the neutral FW accounted for between 53% and 64% of the contribution for each crop. This highlights the important role that nitrogen management plays in determining the overall environmental impact of agricultural systems, reinforcing the need for sustainable practices that minimize nitrogen losses and associated emissions [48]. Other agricultural activities (tillage, planting, and harvesting) contributed mainly to the categories of FRS, FW ecot, HCT, HnCT, IR, LU, M ecot, M eutro, MRS, TE, and WC, due to the usage of diesel in the tractor. In the case of LU, it was due to the number of seeds used in sowing. The contribution of manure collection, biofertilizer transport, and AD is negligible (less than 0.31% on average). The exception is AD, showing a 30% attribution in the WC category, mainly attributed to the water consumption for diluting the manure. Furthermore, the environmental impacts of the digester are negligible, contributing on average 0.7% to all midpoint categories.

Figure 3 shows the contribution of each agricultural stage to the environmental impacts under Scenario 2. The fertilizer application stage was the main contributor in the categories of FPM, FW eutro, GW, OFHh, OFTe, SOD, and TA. Similarly to Scenario 1, the high contribution is mainly attributed to nitrogen field emissions, as well as nutrients that leach

and are carried into the waters. The second main contributor is the production of urea mainly to the categories of FRS, FW ecot, M ecot, TE, and WC, due to the emissions that were generated during production. A similar trend was reported by Katiyar and Gedam [49], where urea production presented the greatest impact in the categories of FW ecot, FW eutro, TE, HnCT and GW. Agricultural activities were identified as the main contributor to HCT, HnCT, LU, and M eutro categories, primarily due to diesel consumption by the tractor. Finally, urea production and agricultural activities contributed almost equally to the IR and MRS categories, attributable to the resources required for their production and the pollutants emitted during the production or use of diesel.

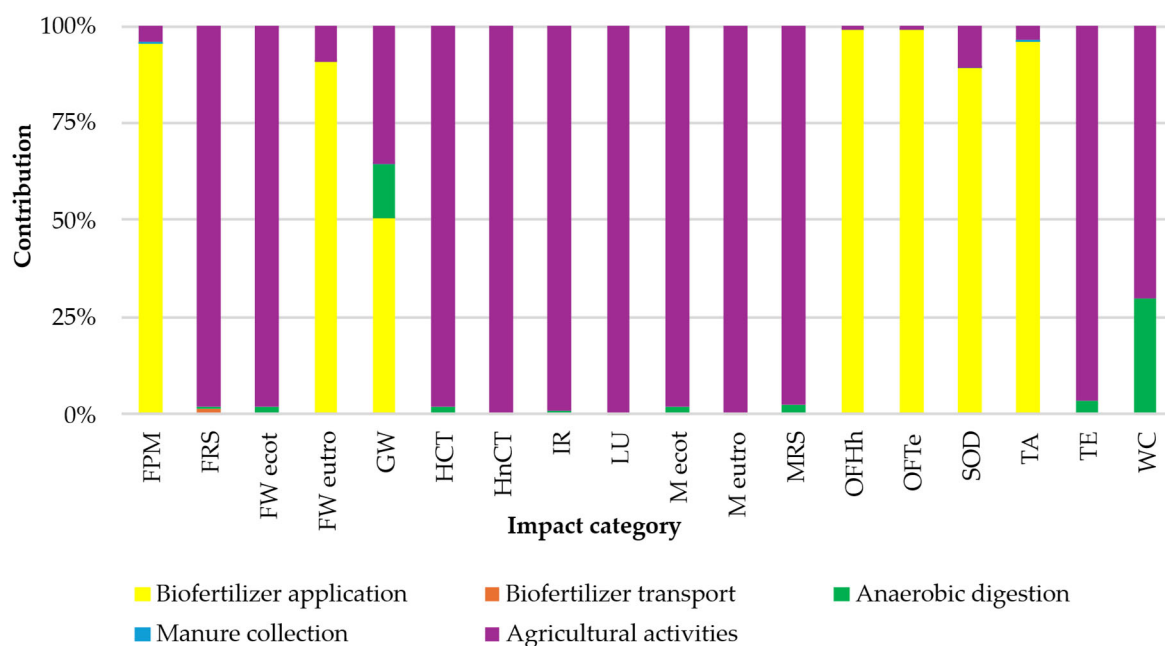


Figure 2. Contribution to environmental impact across production stages under Scenario 1.

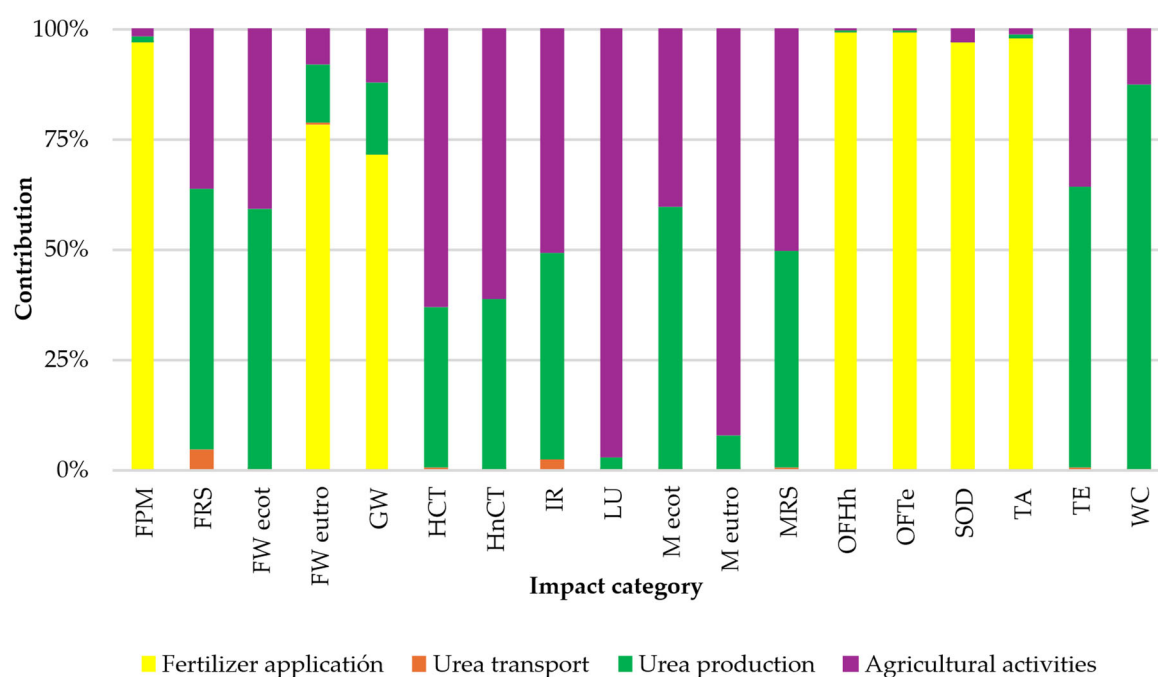


Figure 3. Contribution to environmental impact across production stages under Scenario 2.

Finally, Figure 4 shows the contribution of each agricultural stage to the environmental impacts under Scenario 3. According to this figure, most categories followed a similar trend as Scenario 1; the impacts of agricultural activities predominated as the primary contributor of environmental impacts in 11 of the 18 categories assessed. Meanwhile, direct field emissions were the primary contributor in FPM, FW eutro, GW, OFHh, OFTe, SOD, and TA categories.

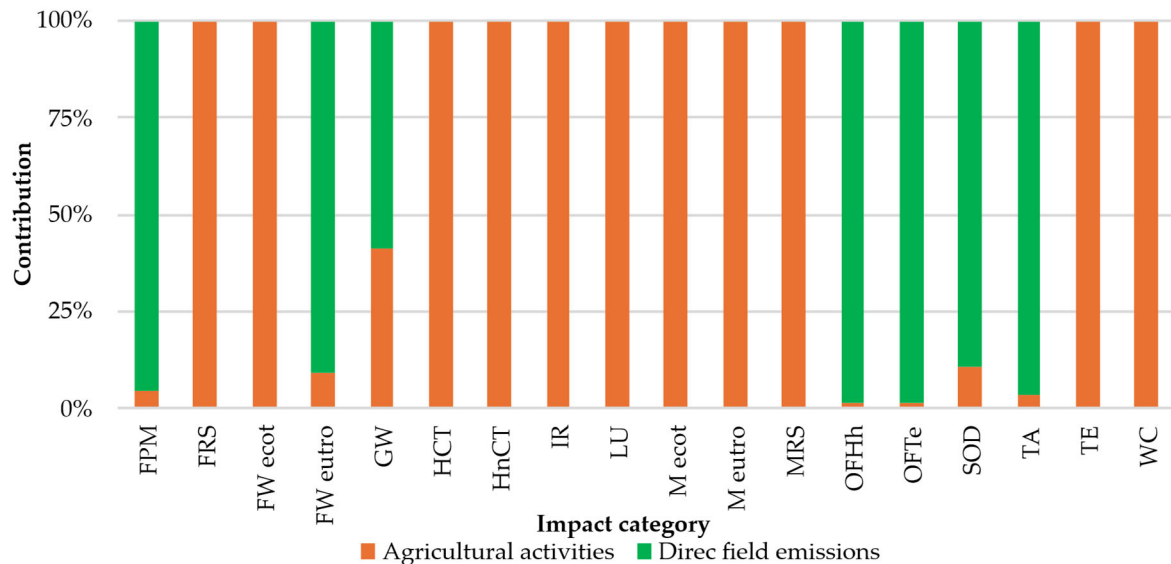


Figure 4. Contribution to environmental impact across production stages under Scenario 3.

3.2. Influence of the Functional Unit on Environmental Impacts

The production of one ton of forage oats is the most used FU since it is easier to understand [50]. Although this FU serves as a basis to analyze the impact of the different stages in each scenario, it is also important to analyze environmental impacts per area (ha) in order to disconnect the yield of forage oats. Table 2 presents the environmental impact results for the eighteen categories, the three scenarios, and the two FUs.

Table 2. Environmental impacts of forage oat production by mass (one ton) and area (one ha) functional unit.

Impact Category	Unit	Impacts of One Ton of Forage Oat Production			Impacts of One Hectare of Forage Oat Production		
		Sc. 1	Sc. 2	Sc. 3	Sc. 1	Sc. 2	Sc. 3
FPM	kg PM _{2.5} eq	1.28×10^0	4.14×10^0	1.82×10^0	9.00×10^0	2.57×10^1	8.94×10^0
FRS	kg oil eq	9.22×10^0	2.86×10^1	1.30×10^1	6.50×10^1	1.77×10^2	6.39×10^1
FW ecot	kg 1,4-DCB	1.11×10^0	3.03×10^0	1.56×10^0	7.85×10^0	1.88×10^1	7.68×10^0
FW eutro	kg P eq	6.76×10^{-2}	8.89×10^{-2}	9.68×10^{-2}	4.77×10^{-1}	5.51×10^{-1}	4.76×10^{-1}
GW	kg CO ₂ eq	8.01×10^1	2.62×10^2	9.81×10^1	5.64×10^2	1.62×10^3	4.82×10^2
HCT	kg 1,4-DCB	3.27×10^0	5.77×10^0	4.60×10^0	2.30×10^1	3.58×10^1	2.26×10^1
HnCT	kg 1,4-DCB	5.49×10^1	1.01×10^2	7.81×10^1	3.87×10^2	6.26×10^2	3.84×10^2
IR	kBq Co-60 eq	6.80×10^{-1}	1.50×10^0	9.64×10^{-1}	4.79×10^0	9.33×10^0	4.75×10^0
LU	m ² a crop eq	2.12×10^1	2.48×10^1	3.04×10^1	1.50×10^2	1.54×10^2	1.50×10^2
Mecot	kg 1,4-DCB	1.44×10^0	3.99×10^0	2.02×10^0	1.02×10^1	2.47×10^1	9.95×10^0
Meutro	kg N eq	5.68×10^{-2}	6.99×10^{-2}	8.14×10^{-2}	4.00×10^{-1}	4.33×10^{-1}	4.00×10^{-1}
MRS	kg Cu eq	1.41×10^{-1}	3.09×10^{-1}	1.96×10^{-1}	9.92×10^{-1}	1.91×10^0	9.66×10^{-1}
OFHh	kg NOx eq	1.14×10^1	3.39×10^1	1.63×10^1	8.04×10^1	2.10×10^2	8.01×10^1
OTe	kg NOx eq	1.14×10^1	3.39×10^1	1.63×10^1	8.04×10^1	2.10×10^2	8.01×10^1
SOD	kg CFC11 eq	1.67×10^{-3}	7.14×10^{-3}	2.38×10^{-3}	1.18×10^{-2}	4.43×10^{-2}	1.17×10^{-2}
TA	kg SO ₂ eq	4.28×10^0	1.57×10^1	6.08×10^0	3.02×10^1	9.75×10^1	2.99×10^1
TE	kg 1,4-DCB	9.41×10^1	2.90×10^2	1.30×10^2	6.63×10^2	1.80×10^3	6.40×10^2
WC	m ³	3.69×10^{-1}	2.36×10^0	3.70×10^{-1}	2.60×10^0	1.46×10^1	1.82×10^0

Note: Sc. 1 production with biofertilizer, Sc. 2 conventional production, Sc. 3 production without fertilizers.

Regardless of the FU, Scenario 2 presented the highest impacts because inorganic fertilizer production and field emissions were generated from the field–fertilizer interaction.

In agricultural LCA studies, field emissions from nitrogen fertilizers are a significant concern, since their usage generally leads to adverse environmental impacts across air, water, and soil. Therefore, minimizing inorganic N-fertilizer application has been recognized as essential for decreasing N_2O and NO_x emissions [51]. The transport of urea was only responsible for 1 to 3% in some environmental impact categories, making it negligible, as mentioned by Hasler et al. [52]. Conversely, Scenario 3 generated the lowest environmental burden for the area-based FU, because it involved no additional production or transport of inputs. In addition, field emissions were lower compared with those associated with the use of inorganic fertilizers. In contrast, the impacts in Scenario 1 were slightly higher than in Scenario 3 due to the burdens related to the construction of the biodigester and the production of the biofertilizer. Therefore, from an environmental perspective, using self-produced biofertilizers avoids unnecessary transport activities while promoting resource conservation, reducing pollution, preserving biodiversity, and reducing fossil fuel use [53].

To compare the magnitude of the differences in environmental impacts among the different impact categories, Scenario 1 was used as the reference (100%) for each FU. The results were then compared with Scenario 2 (Figure 5) and Scenario 3 (Figure 6). This approach provides a clear perspective on the relative differences between each scenario. For both FUs, mass and area, Scenario 2 showed greater impacts for most categories, reaching up to six times higher than Scenario 1 as in the case of the WC category. Only LU and M eutro were close to Scenario 1, with a 10% difference among both scenarios. According to Fathollahi et al. [54], the application of inorganic fertilizers contributes to increasing the impact of M eutro; therefore, replacing inorganic N-fertilizer with organic fertilizer can be attributed to the reduction in this study. Similarly, the impact of LU showed minimal differences among the three scenarios, due to the use of the same harvesting area and the same number of seeds. Furthermore, the land area required for the digester was not significant.

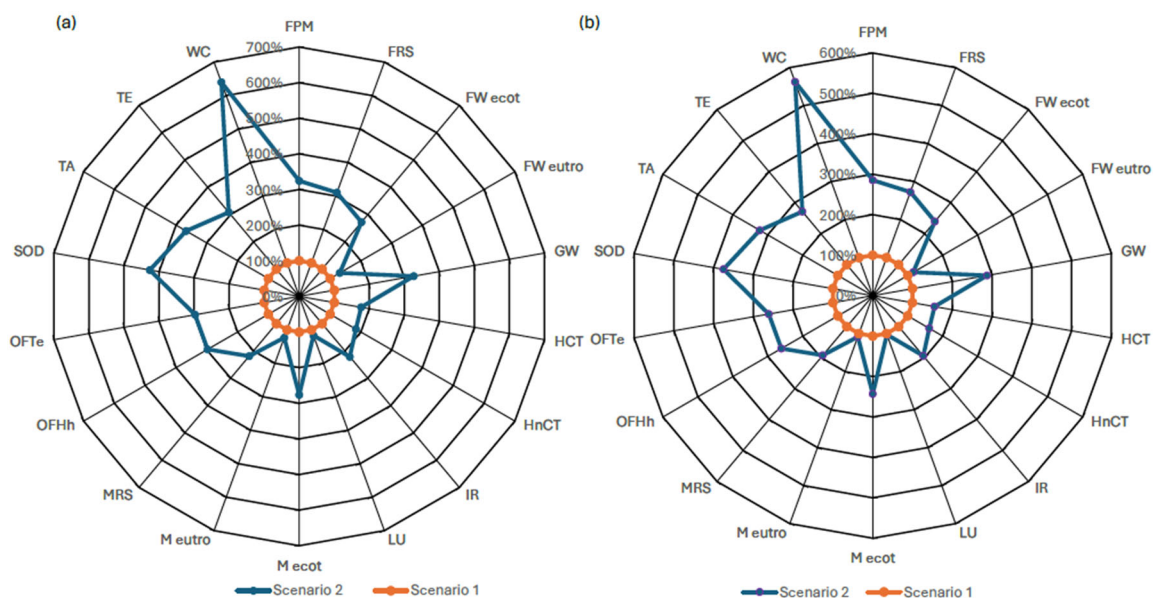


Figure 5. Comparison of the environmental impacts of forage oat production according to Scenarios 1 and 2, considering two FUs: (a) mass-based and (b) area-based.

Figure 6 shows a comparison of Scenarios 1 and 3 using a mass-based FU. The impacts were substantially higher for Scenario 3, at around 40% higher in most categories, except WC and GW, where there was little difference. However, when using an area-based FU, the impacts of Scenario 3 were comparable across nearly all categories with those of Scenario 1.

As in the mass-based FU comparison, the largest difference occurred in WC and GW, where Scenario 3 performed approximately 30% better for WC and 16% for GW. This improvement was attributed to the higher water consumption associated with biofertilizer production and the fugitive emissions, respectively, although the gap was less pronounced than the WC difference observed between Scenarios 1 and 2, where WC was about 500% higher than in Scenario 1. Therefore, although both scenarios show similar water impacts when assessed using a mass-based FU, Scenario 3 demonstrates better water efficiency when evaluated using an area-based FU. However, when using the mass-based FU of forage oat production, Scenario 3 generates greater environmental impacts. This was attributed to the low production of Scenario 3 (4.92 t/ha) compared to Scenario 1 (7.05 t/ha).

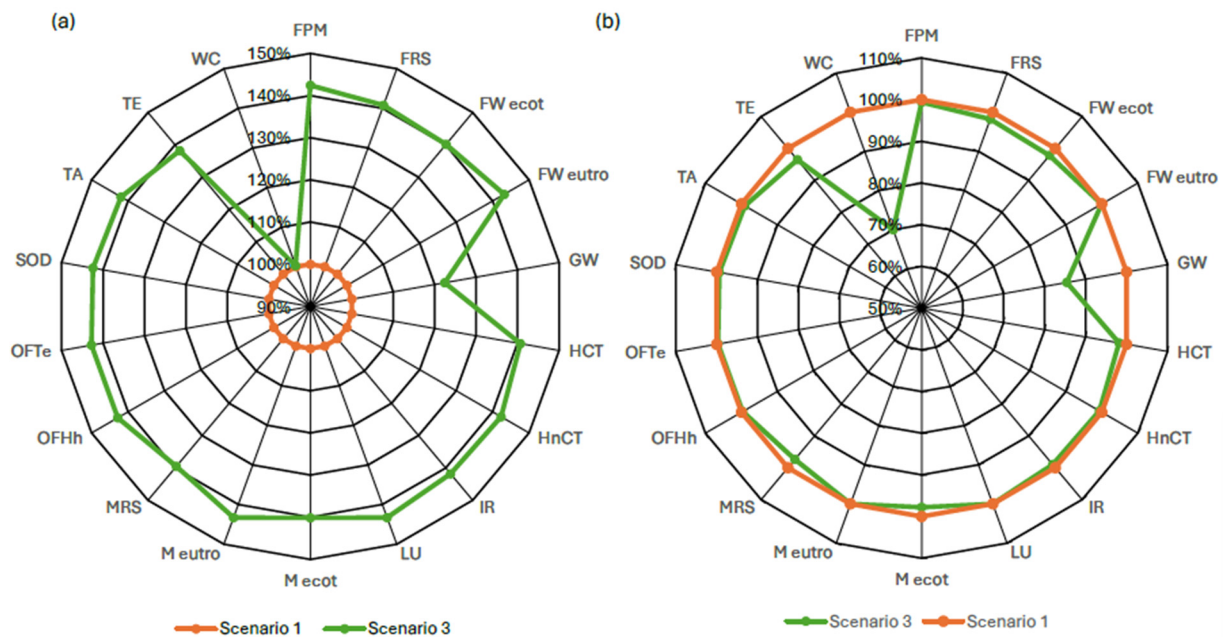


Figure 6. Comparison of the environmental impacts of forage oat production according to Scenarios 1 and 3, considering two FUs: (a) mass-based and (b) area-based.

4. Discussion

The current literature concerning the environmental impacts of oat production primarily addresses either its grain production or its integration within the LCA of livestock production [30]. In fact, no peer-reviewed LCA studies addressing the environmental impacts of forage oats have been identified. Viana et al. [23] found similar results when using different FUs. Authors examined oat production in organic and conventional systems using three FUs: one ton, one ha, and 1000 Canadian Dollars (CAD). Their findings indicated that the evaluation of organic versus conventional agriculture was significantly affected by the unit of analysis chosen. Using mass-based FUs, such as one ton, helps to identify more efficient systems but can also downplay regional impacts. In contrast, area-based FUs often reveal practices that mitigate environmental pressure. These results are similar to those of our study, which found that the environmental impacts of conventional production were higher compared to organic production, leading to a significant difference in environmental terms. According to our findings, using the area-based FU of oat production without any fertilization applied resulted in the lowest environmental impact across all evaluated categories. However, this scenario also yielded the least production compared to the other two scenarios. Conversely, when using a mass-based FU, the best environmental and production outcomes were associated with the use of biofertilizer (Scenario 1), because its production yield is higher than when no fertilization was applied (Scenario 3).

As mentioned in Section 1, no previous LCA studies analyzing the production of forage oat were found. In this context, regarding the environmental impacts of equivalent products, Rodrigues-Viana et al. [26] measured the environmental burdens of oat flake production in northeastern Canada. The authors concluded that the use and production of inorganic fertilizers represented at least 50% of the environmental impacts assessed in oat flake production. These results are consistent with the results obtained in Scenario 2 when inorganic N-fertilizers were used; N-fertilizer production and application were identified as the main activities contributing to environmental impacts (see Figure 3). Hietala et al. [29] evaluated the GW of various forage productions in Finland, including oats. Using two life cycle impact assessment methods—IPCC and Product Environmental Footprint—the authors found a GW value of 0.63 kg CO₂ eq/kg and 0.58 kg CO₂ eq/kg, respectively. These values are larger than those reported in the current study, primarily due to the lower oat yield (4 t/ha) and the inclusion of emissions from manure application as a supplement to nitrogen fertilization. They concluded that the main contributors to GW of forage crop production in Finland were energy and input production, along with nitrogen emissions, which aligned with the findings of this research. In fact, in this research, N emissions resulting from fertilizer applications as well as those generated during production itself constitute the main source of nitrogen emissions. NO₃ and NO₂ emissions are similar in Scenario 1 and Scenario 3 (Table S5) because the biofertilizer used in Scenario 1 adds little N to the field. The main drivers of these emissions are soil characteristics and emissions related to the crops. On the contrast, Scenario 2 considered the highest N-fertilizer input. However, the yield of this Scenario is lower than in Scenario 1, which can be attributed to the foliar application of the biofertilizer. This supplies not only N, but also other essential nutrients that are absorbed through the leaves and transported to the roots and the rest of the plant. There, they stimulate root activity and biomass development. Specifically, the absorbed N and P accumulate in areas of active growth, such as new leaves and developing stems, thereby boosting production [55]. In contrast, Bashyal et al. [56] studied small-scale rice production systems, showing that higher levels of mechanization and greater input intensity can improve yield and energy efficiency, although they may also increase emissions. In addition, regional differences in mechanization practices, diesel consumption, and fertilizer use significantly influenced both productivity and emissions. This could help to reduce environmental impacts when assessments are performed per mass-based FU; however, impacts would increase when evaluations are conducted per area-based FU.

Finally, an important issue in the agricultural context is the variability of environmental impacts due to different factors, such as management practices and agro-climatic conditions. In this context, a sensitivity analysis of fugitive emissions and oat productivity was performed. In Scenario 1, increases in fugitive emissions from the assumed 1.3% (see Section 2.3.2) to 5% and 10% were evaluated. The environmental impact categories affected were GW, which increased by 40% and 94%, respectively, and TE, which increased by 1.9% and 4.5%, respectively. Although these values remained lower than those obtained for Scenario 2, the comparison with Scenario 3 showed different results. Using a mass-based FU, the GW category value in Scenario 3 was lower than that of Scenario 1. This could indicate that fugitive emissions are a key parameter influencing GW. On the other hand, by increasing oat productivity by 10%, 20%, 50%, and 100% relative to the levels evaluated in Scenario 3, different performance is obtained. When productivity in Scenario 3 increases by 10% and it is compared with Scenario 1, no environmental impact category showed lower values than those in Scenario 1. However, with a 20% increase, only the LU category was lower. With a 50% increase, FW Eutro and M Eutro also began to show lower values, and with a 100% increase, HCT and HnCT likewise decreased. The detailed results are presented in Table S6.

This research underscores the benefits of utilizing biofertilizers as an alternative to unprocessed manure as an organic fertilizer. While unprocessed manure does offer some advantages over chemical fertilizers, it is associated with higher environmental impacts. Transforming manure into biofertilizers mitigates these impacts while still providing essential nutrients for crop production, showcasing a more sustainable method of fertilization in agricultural practices [57]. Additionally, the findings of this research offer a clearer understanding of the environmental impacts associated with the evaluated FUs. By utilizing data obtained directly from the field, this study enhanced the reliability and accuracy of agricultural LCAs, ensuring that the results reflected real-world conditions and practices. This approach contributed to a more robust framework for assessing the sustainability of agricultural practices, particularly in relation to the use of biofertilizers in forage oat production.

5. Conclusions

This study analyzed the environmental implications of the on-farm use of biofertilizer derived from cow manure to produce forage oat using the life cycle assessment (LCA) methodology. Considering a cradle-to-farm-gate system boundary and two functional units (FUs), one ton of produced oat (mass-based) and one hectare of harvested oat (area-based), three scenarios were evaluated: (i) biofertilizer application, (ii) inorganic fertilizer application, and (iii) a control strategy without fertilization.

The results indicate that using biofertilizer reduces the environmental impact of forage oat production compared to chemical fertilization, regardless of the selected FU. However, comparisons between the environmental burden of biofertilizer and the unfertilized scenario depend heavily on the chosen FU. Under the mass-based FU, biofertilizer application results in lower environmental impacts than the control strategy, whereas the unfertilized scenario may show comparable or lower impacts in some categories when the area-based FU is considered. These discrepancies may be derived primarily from the higher yield when biofertilizer is used compared with an unfertilized strategy. Therefore, reporting both mass- and area-based FUs is highly recommended.

These findings suggest that further efforts should be directed toward utilizing livestock manure as an input for producing the farm's own forage, thereby stimulating circular agricultural practices. Using manure as a biofertilizer not only mitigates environmental impacts compared to inorganic alternatives, but could also reduce production costs for farmers by decreasing the need for buying commercial agrochemicals while simultaneously achieving similar yields. However, these results should be interpreted with caution, as further sensitivity and uncertainty analysis are needed to explore key parameters. These include biofertilizer nutrient content, nitrous oxide emission factors, transport distance, digester lifespan, manure management baselines, and biogas handling. Therefore, future research should address the uncertainty and variability associated with these parameters, as well as the broader economic and social implications of these agricultural management practices.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture16151653/s1>, Table S1: Monthly temperature and precipitation for 2023–San Francisco del Mezquital weather station 10065 [33]; Table S2: Soil parameter extract to Aguirre-Córdova et al. [34]; Table S3 Biofertilizer chemical composition; Table S4: Nitrogen (N) and phosphorous (P) supplied per ha; Table S5: Total nitrogen emissions from the scenarios according to Indigo-Nv3; Table S6: Comparison of Scenario 1 with the production increase from the sensitivity analysis.

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analysis: O.F.A.-C. and L.V.-I.; Writing—original draft: O.F.A.-C., L.V.-I. and G.A.P.-C.; Writing—reviewing and editing: R.V.V., I.A.O.S. and J.A.C.S. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic Digestion
CH ₄	Methane
CO(NH ₂) ₂	Urea
CO ₂ eq	Carbon dioxide equivalent
FAO	Food and Agriculture Organization
FPM	Formation of Particulate Matter
FRS	Fossil Resource Scarcity
FU	Functional Units
FW ecot	Freshwater Ecotoxicity
FW eutro	Freshwater Eutrophication
GHG	Global Greenhouse Gas
GW	Global Warming
HCT	Human Carcinogenic Toxicity
HDPE	High-Density Polyethylene
HnCT	Human non-Carcinogenic Toxicity
IPCC	Intergovernmental Panel on Climate Change
IR	Ionizing Radiation
ISO	International Organization for Standardization
K ₂ O	Potassium oxide
LA	Latin America
LCA	Life Cycle Assessment
LU	Land Use
M ecot	Marine ecotoxicity
M eutro	Marine eutrophication
MRS	Mineral Resource Scarcity
N	Nitrogen
N ₂ O	Nitrous oxide
NH ₃	Ammonia
NH ₄	Ammonium nitrogen
NO	Nitrogen monoxide
NO ₃	Nitrate
Nox	Nitrogen Oxides
OFHh	Ozone Formation Human health
OFTe	Ozone Formation Terrestrial ecosystems

P	Phosphorus
P ₂ O ₅	Phosphorus pentoxide
SALCA	Swiss Agricultural Life Cycle Assessment
SOD	Stratospheric Ozone Depletion
TA	Terrestrial Acidification
TE	Terrestrial Ecotoxicity
WC	Water Consumption

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